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Determining the scale of R&D investment for renewable energy in Korea using a comparative analogy approach

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ABSTRACT

The rising price of fossil energy due to increasing global energy consumption has stimulated investment in renewable energy. Despite Korea's high dependence on foreign energy sources, it is well behind other developed countries with regard to renewable energy production. This study attempts to develop a reasonable R&D investment plan based on the forecasted diffusion of renewable energy in the Korean market by analyzing the experiences of other developed countries. The German market is selected as the reference case on the basis of its similarity to the Korean market. The realized data indicate that the growth of technology is proportional to cumulative R&D investment. A final investment schedule is established based on the goal of meeting the target penetration level. The suggested investment plan, which differs substantially from the plan recently announced, indicates the necessity of more active investment in early stage and supportive policies for R&D into renewable energy.

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1. Introduction

Rapid industrialization of developing countries like China and continuous global economic growth has led to a drastic increase in global energy consumption. According to the "World Energy Outlook 2012" [1], global primary energy consumption is predicted to increase by more than 33% through 2035, and daily global oil

consumption is expected to increase from 87.4 million barrels in 2011 to 99.7 million barrels in 2035, which would result in a price increase to $125 per barrel (in 2011 dollars). The global petroleum market has experienced a trend of rising prices; from $25 per barrel in 2001 to $98 in 2007, and recent spot prices have exceeded $100 [2]. This price increase could potentially affect Korea more severely than other countries, because Korea is not only one of the world's largest energy consumers (8th in total primary energy and 7th in oil), but is also a resource-poor country that imports more than 97% of total energy resources.

The rising price of fossil energy caused by the sharp increase in global energy consumption has focused attention on renewable energy as an alternative energy source. This increased focus has led to various supranational efforts such as 'Sustainable Energy for All' [3] and the 'Earth Summit in Rio de Janerio' [4], and many countries have started to develop relevant policies and invest in necessary facilities and R&D. Decades of efforts have achieved results to some degree. In 2011, the global investment in renewable energy reached $257 billion, which is 17% higher than that in 2010. Above all, renewable energy accounted for 44% of the newly added global generation capacity in 2011.

However, unlike advanced countries that have made dedicated efforts to develop renewable energy for more than 30 years, Korea still shows disappointing indicators regarding renewable energy. As of 2011, the contribution of renewable energy to total primary energy consumption in Korea was only 2.75% [5], which is far lower than the global average of 6%, including both developed and developing countries [6]. Beyond OECD countries, several developing countries such as China and India are far ahead of Korea in renewable energy. China is in a race with the United States to be the leading investor in renewable energy, and India has achieved the world's steepest growth in renewable energy with an investment of $12 billion in 2011, 62% higher than the previous year [6]. To reform the situation, the Korean government announced a $37.1 billion budget ($30 billion for technical supplies and $7.1 billion for development) as part of a master plan to escalate investment in renewable energy with the goal of a renewable energy penetration rate of 11% (3.03 TOE) [7].

However, experts and opinion leaders in the energy industry have raized concerns about the viability of the plan. Specifically, one of the most controversial questions is whether the amount of investment planned is sufficient to ensure that the target renewable energy penetration rate is achieved. It has been argued that the scale of investment seems insufficient compared to that of other countries, and that it is necessary to reexamine what the investment budget should be to achieve the goal of an 11% penetration rate of renewable energy by 2030. The present paper is motivated by this argument, which is critical to the success of the development of renewable energy in Korea.

To estimate the appropriate scale of investment to meet the target penetration level of renewable energy in a systematic manner, several factors should be considered, such as the cost drivers of technology development, diffusion processes, technological uncertainty, and market success. This is a complicated task requiring forecasting of the technology diffusion process and a good understanding of the relation between investment and the renewable energy penetration rate. As a first step, we examine the technology diffusion process. Generally, the diffusion process of a technology exhibits an S-shaped pattern [8,9], and is thus suitable for diffusion curves based on logistic [10], Gompertz [11], and Bass models [12]. Studies on the diffusion of renewable energy have been conducted with a variety of methods since the late 1990s. Jacobsson and Johnson [13] proposed an analytical framework to describe the transformation process of renewable energy technologies from the perspective of innovation. Painuly [14] investigated barriers to the diffusion of renewable energy penetration, and

suggested country-by-country measures to overcome the identified barriers. There have also been attempts to utilize the diffusion process to forecast the future of renewable energy, such as the study of Purohit and Kandpal [15], who forecast irrigation water pumping in India based on four diffusion processes of other renewable energy technologies.

Diffusion of energy technologies also possesses a unique quality that often resembles that of precedents. Precedents include two different categories: primitive or previous technologies that exist in the same market, and the same technology that previously prevailed in more developed markets or countries. One of the most remarkable studies on this topic is by Grübler et al. [16], who conducted a comparative analysis of various energy technologies across countries. They argued that diffusion patterns of a technology in different markets were similar, and thus it was reasonable to consider a connection between these patterns. This emphasizes the importance of investigating cases of developed or advanced countries and making predictions based on the experiences of these countries when forecasting the diffusion process of energy technologies.

A critical recent advance is an understanding of the relation between diffusion and investment. Tsoutsos and Stamboulis [17] argued that a successful policy for renewable energy should be based on identifying its innovation process. Popp et al. [18] analyzed diffusion patterns and the impact of technological change on investment in renewable energy in many countries by counting patents. Pettersson and Soderholm [19] investigated the effectiveness of climate policy and future investments in Sweden. Similarly, Aslani et al. [20] studied policies and achievements in renewable energy based on data from Nordic countries. More broadly, Rao and Kishore [21] conducted an in-depth review of the various diffusion models applied to renewable energy to assess the impacts of these policies. Above all, Grübler et al. [16] argued that diffusion patterns of new technologies resemble those of existing technologies by observing various energy technologies, which provides the basis for an analogous approach to estimate a renewable energy diffusion process. In support of Grübler and colleagues' findings, Pettersson and Soderholm [19] argued that technological learning in the Swedish power sector was strongly related to R&D spillover.

Nevertheless, to the best of our knowledge, the analogy approach has not been used in combination with renewable energy diffusion. This is surprising, because numerous other studies have used this methodology, e.g. Thomas [22] and Mahajan et al. [23]. Considering the prevalence and effectiveness of the guess-by-analogy method in the absence of enough data [24], it is worthwhile to apply the analogy approach to the renewable energy diffusion process to determine a reasonable investment policy in renewable energy for Korea.

The breadth of related work is relatively narrow in Korea. Hwang et al. [25] found that inconsistent or untimely policies had a negative impact on penetration rates of renewable energies, and forecast future penetration levels through diffusion models. Park et al. [26] predicted the grid parity of solar photovoltaic energy based on two factors from a learning curve model that considered supporting policies and R&D investment plans in Korea. Kim [27] analyzed the diffusion process of renewable energy penetration and R&D investment in Korea utilizing the German case as an analogy. Ku and Yoo [28] provided a basis for renewable energy policymakers by assessing benefits with a choice experiment at an individual level. However, Korean studies have mostly focused on analysis of historical data, whereas many foreign studies have undertaken to understand and forecast diffusion patterns of renewable energy. Thus, there is a paucity of studies on forecasting the diffusion process and estimating the required scale of investment in renewable energy in Korea.

Our purpose in this study was to forecast the penetration rate of renewable energy and determine a reasonable scale for R&D investment in renewable energy in Korea based on the relationship between diffusion and R&D investment drawn by analogy from empirical cases of advanced countries. Among numerous candidate developed countries, we choose the German market based on the similarity of its diffusion patterns to those of the Korean plan. We then determined how investment triggered the growth of technology from the selected benchmark, and applied the *S*-curve relation formula to derive an appropriate investment plan for Korea. The present paper is a pioneering attempt to forecast the diffusion process of renewable energy technology in Korea by comparative analogy with the case of an advanced country. Our reasons for adopting this methodology owe much to the findings of Grübler et al. [16].

The remainder of this paper is organized as follows. We briefly describe diffusion models and the analysis framework in Section 2. In Section 3, we establish a projected R&D investment plan by analogy with the German case. Finally, we present our conclusions in Section 4 and discuss future research directions.

2. Brief overview of renewable energy in Korea

It is worthwhile to review the current status of renewable energy and policies regarding related industries in Korea. As one of the major industrialized countries, overall primary energy consumption has been increasing constantly up to 271.4 million TOEs in 2011 [5]. Petroleum and coal account for more than two thirds of whole primary consumption; the third largest source is liquid natural gas (LNG) as shown in Fig. 1. In contrast, renewable energy accounted for only 2.3% of primary consumption at 6.4 million TOEs as of 2011. In addition to the current dependency on fossil fuel energy, the Korean government predicted that the demand for petroleum-based energy sources would increase continuously over the next 5 years [29].

Given Korea's significant dependency on imported energy sources, it is unsurprising that the economy tends to suffer from fluctuations in energy prices. After the historic oil shocks in the 1970s, the Korean government recognized the need to build a foundation for a stable, long-term energy supply. Therefore, the history of R&D investment in renewable energy began with the "Development of Alternative Energy Act" in 1988; the Ministry of Trade, Industry and Energy had invested more than $870 million across 11 sectors, including photovoltaic cells and wind power, by 2009.

Currently, however, Korea is just in the beginning stages of renewable energy usage. As of 2010, only 2.6% of total primary energy consumption was covered by renewable energy sources [5].
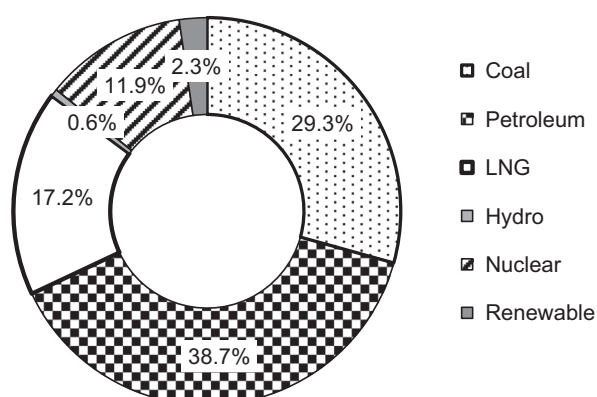

Fig. 1. Penetration rates of different sources of primary energy.

Among various kinds of renewable energy sources, waste energy accounted for more than half with 5.1 million TOEs (67.4%). Bio-energy (including biogas and biodiesel) and hydropower followed, accounting for 13.0% and 12.8% of the renewable energy used. From a technological perspective, core technologies in solar thermal, solar photovoltaic cell, and bio and waste energies have been well developed and commercialized to such an extent that their levels are close to those in other advanced countries. In other areas, however, technological levels remain in the basic application stages. The overall level of renewable energy technologies in Korea was evaluated as 77% that of advanced countries; 87% for solar photovoltaic cells, 81% for wind power, and around 70% for hydrogen fuel cells.

To improve the situation and boost the renewable energy industry, the Korean government developed a master plan for investment in renewable energy with a budget of $7.1 billion. Solar thermal and solar photovoltaic technologies are the primary energy sources that will receive attention. This selection is mainly due to the relatively advanced existing technologies. Energy from waste, including refuse-derived fuel, is also highlighted in the investment plan, because this has become a leading alternative energy source in Korea. Other than those technologies, the geothermal sector attracted some interest as recent studies have highlighted the potential of deep geothermal energy.

The government plan aims to commercialize these technologies and was designed to support R&D projects related to essential major tasks selected by authorities. Additionally, the program is intended to trigger private investment by various means such as investment funds initiated by the government and deregulations.

3. Methodology

3.1. Analysis framework

Our aim was to forecast the diffusion of renewable energy and thus establish a reasonable investment plan based on the forecast. However, as previously stated, the Korean renewable energy market is not sufficiently developed for a proper quantitative analysis. To address this, we utilized the 'Co-evolution' concept of Grübler et al. [16], which refers to the observation that diffusion of a technology or related energy sources and infrastructure in a follower country usually follows the same pattern as that seen in a leader or a developed country. Therefore, we gathered diffusion data for the investment and penetration rate in developed countries to apply the guess-by-analogy method.

The overall analysis framework and its sequence are illustrated in Fig. 2. The procedure begins with the renewable energy penetration set by the Korean government as the target value. Based on the estimated diffusion process of the Korean plan, we chose a benchmark developed country whose realized diffusion pattern was most similar to what we expected Korea's to be. Next, we analyzed the relation between investment and the resulting penetration rate of renewable energy using data from the selected country. Finally, we obtained an investment plan for Korea by applying the relations determined for the benchmark country to the expected diffusion curve of renewable energy in Korea.

3.2. Logistic model

Foster [8] noted that diffusion of a technology follows a S-shaped curve, which is consistent with general diffusion models. Among various representative diffusion models, the logistic model and the Bass model are the most popular. The Bass model [12] facilitates interpretation of diffusion patterns is a flexible model [30]. However, the logistic model usually outperforms other diffusion models
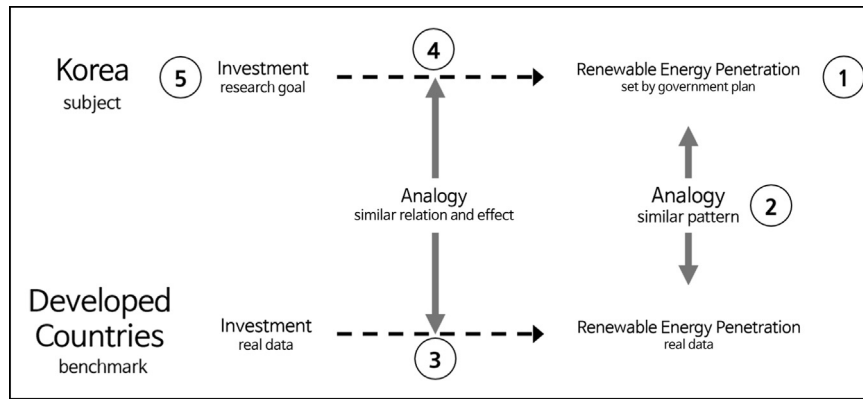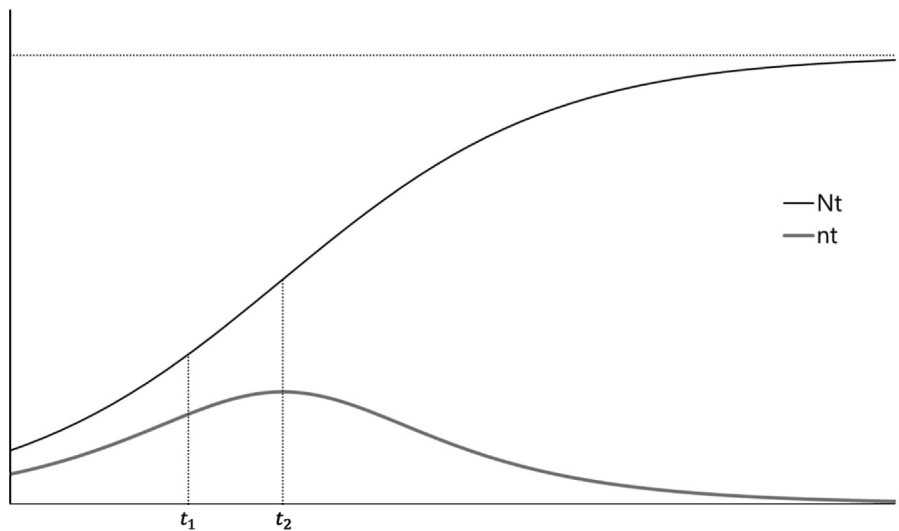
Fig. 2. Analysis framework.

Fig. 3. Example of logistic curves.

in terms of estimation fitness and forecasting accuracy due to its parsimony and flexible y-intercept [24,30].

The logistic model (or logistic growth curve) describes innovation diffusion using three parameters: m to represent market potential, a as the y-intercept parameter, and b as a parameter that determines the speed of diffusion:

$$N(t) = \frac{m}{1 + e^{a+bt}}, \tag{1}$$

$$n(t) = -\frac{mbe^{a+bt}}{\left(1 + e^{a+bt}\right)^2}, \tag{2}$$

where $n(t)(N(t))$ denotes the (cumulative) adopters or growth level at time t. Examples of logistic curves are provided in Fig. 3. As shown in the cumulative (upper) curve, market potential is an asymptotic limit for the number of cumulative adopters. There are also two tipping points, called takeoff (t_1) and peak (t_2), which are defined as the early inflection point and the maximum point of the net growth curve, respectively.

The logistic model is also appropriate to investigate the relation between investments and the penetration rate of renewable energy. Afuah [9] reported that diffusion of technology (renewable energy in our case) has an S-shaped curve as an output of investment. Therefore, a logistic model with the input variable of investment rather than time would appropriately model the investment–technology relationship.

3.3. Data

3.3.1. Diffusion of renewable energy

Annual renewable energy penetration rates in OECD countries were collected from the series "Energy Balances of OECD Countries" [31,32]. The collection period was from 1990 to 2012, and countries listed in reports in both 2010 and 2013 were selected.

Fig. 4 shows country-by-country trends of renewable energy penetrance in all 29 OECD countries. Most countries have penetration rates below 40%, while in Iceland the rate exceeds 70% because its natural environment is suitable for geothermal power generation.

3.3.2. Investment

Annual investment trends in OECD countries (a key factor in fostering a technology) were collected through "International Energy Agency Data Services" [33]. Data are reported in US dollars at the 2012 exchange rate. Because the GDP scales differed, we transformed them into ratios based on annual GDP trends.

4. Analysis and results

4.1. Selecting the benchmark country

Our first analysis step was to find the most appropriate country to use as a benchmark for Korea. We based this selection on the
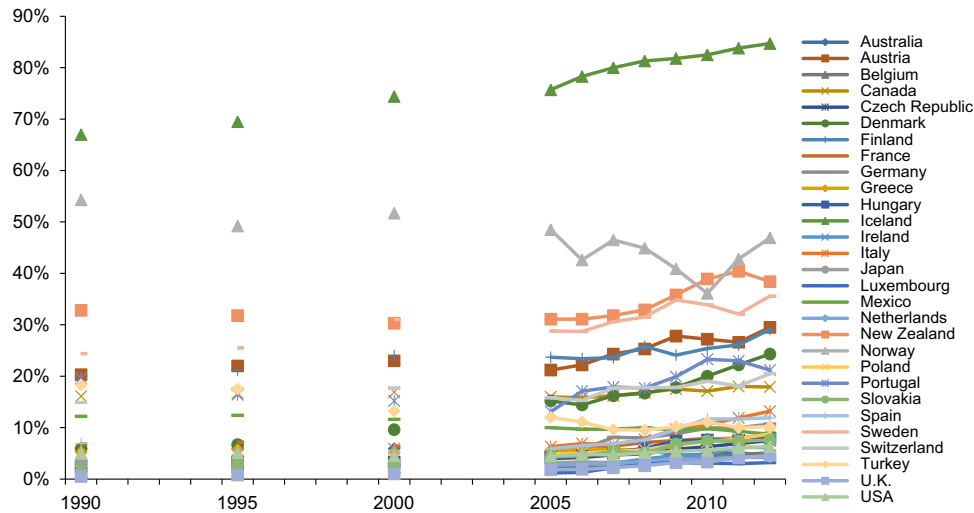
Fig. 4. Penetration rates of renewable energy in OECD countries.

basis of similarity in diffusion patterns. First, we identified the diffusion pattern of the penetration rate of renewable energy in Korea. These data were derived from "The 3rd Master Plan for Technical Development and Supply of New and Renewable Sources of Energy" [7] and realized data from the government report "2012 New & Renewable Energy White Paper" [5] and "Energy Balances of OECD" series [31,32], as addressed in Section 2. Combined and arranged diffusion data are summarized in Table 1.

Logistic model in Eq. (1) was estimated using the nonlinear least square (NLS) method with an upper limit of 1 (100%) for the market potential m. Estimation results are shown in Table 2 and Fig. 5.

The estimated logistic model fit the data with high accuracy as shown in the curve. The forecasted trend grew consistently, exceeding the target level by 11% as announced in the government plan.

In sequence, realized data in other OECD countries were also estimated to choose the benchmark. The same logistic model and estimation method were applied, and the estimation results for the 29 countries are summarized in Table 3.

Before comparing the diffusion patterns of OECD countries and Korea, we narrowed down the candidates for convenience. According to their fitness, the 10 countries with 80% or higher adjusted R^2 values were selected. In other words, we did not consider the rest of the countries appropriate for logistic model estimation because of their non-S-shaped diffusion patterns; these countries were therefore excluded from subsequent analyses.

The final choice of the 10 potential benchmark countries was based on two criteria. First, we compared the final target penetration level of Korea and the diffusion patterns of the candidates. As noted above, the Korean government set a target level of 11% by 2030, which is the 22nd year from the announcement of the plan. Therefore, the relative distance between the estimated curve and the target value is a measure of closeness.

Table 4 shows the estimated penetration rates of 10 OECD countries based on the parameters reported in Table 3 and $t = 22$, as well as absolute percentage error against the target value of 11%. It is clear that Germany is the most similar to Korea, with a considerable gap to the second most similar country (Poland). These results are confirmed in Fig. 6, which shows the overall diffusion patterns of the candidates.

Other measure for selection was the similarity in estimated parameters. For the three parameters m, a, and b of the logistic model, we defined the distance between Korea and a candidate

Table 1
Penetration rates of renewable energy in Korea.

Year	Penetration rate (%)	Realized/planned
2009	2.50	Realized data
2010	2.60	Realized data
2011	2.75	Realized data
2015	4.30	Planned
2020	6.10	Planned
2030	11.00	Planned

Table 2
Estimation results for renewable energy in Korea.

a	b	m	ln(SSE)	Adj. R^2
1.981	− 0.110	18.022%	11.995	0.9972

country as follows:

$$\text{distance} = \sqrt{\left(\frac{a_{\text{Korea}} - a_{\text{candidate}}}{\sigma_a}\right)^2 + \left(\frac{b_{\text{Korea}} - b_{\text{candidate}}}{\sigma_b}\right)^2 + \left(\frac{m_{\text{Korea}} - m_{\text{candidate}}}{\sigma_m}\right)^2}$$

(3)

To avoid the distortion caused by different scales of parameters, we divided the difference by the standard deviation σ, calculated from all values of the 10 candidates and Korea.

Distances calculated by Eq. (3) are shown in Table 5; Germany was again the best candidate. It was closest to Korea by a large margin (1.918) compared to the second-best candidate (Denmark).

Based on the results discussed above, we selected Germany as the most appropriate choice as a benchmark. In addition to the statistical results, several other factors indicate that Germany is a good example for Korea with respect to the renewable energy market. First, Germany is the third largest market in investments in renewable energy as of 2009 [5]. Second, the German government has implemented aggressive policies on renewable energy. For example, they set up an early retirement plan for all nuclear plants involving replacement by new energy sources [1]. Moreover, the German government has successfully executed various policies and regulations. One of the most representative incentive programs is the 'Market Incentive Programme (MAP)';
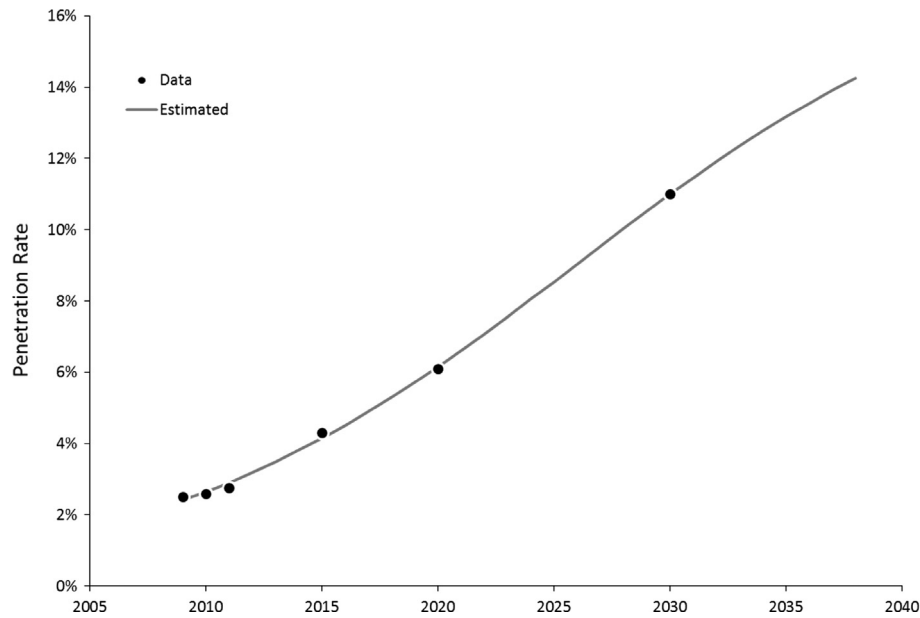
Fig. 5. Estimated logistic curve for renewable energy in Korea.

Table 3
Estimation results for renewable energy in OECD countries.

Country	a	B	m	$\ln(SSE)$	Adj. R^2
Australia	2.329	0.000	0.604	2.032	0.000
Austria	1.447	−0.020	0.999	1.246	0.523
Belgium	5.756	−0.124	0.999	1.100	0.951
Canada	1.582	−0.004	0.933	0.237	0.284
Czech Republic	4.237	−0.072	1.000	1.006	0.930
Denmark	3.136	−0.084	0.998	0.280	0.969
Finland	1.438	−0.018	0.998	0.517	0.692
France	2.145	−0.006	0.607	2.054	0.107
Germany	3.466	−0.152	0.217	1.050	0.960
Greece	3.072	−0.024	0.982	2.259	0.318
Hungary	4.035	−0.069	0.999	1.891	0.845
Iceland	109.238	−110.569	0.847	1.955	0.000
Ireland	5.243	−0.109	0.996	1.939	0.868
Italy	3.641	−0.070	0.997	2.161	0.745
Japan	2.932	−0.009	0.601	1.892	0.264
Luxembourg	4.944	−0.093	0.603	3.029	0.731
Mexico	1.596	0.000	0.609	2.281	0.000
Netherlands	4.291	−0.077	0.605	0.659	0.963
New Zealand	0.883	−0.014	0.999	1.631	0.085
Norway	0.087	0.000	0.959	2.199	0.000
Poland	3.972	−0.067	0.999	1.494	0.880
Portugal	1.699	−0.014	0.996	2.718	0.187
Slovakia	4.340	−0.082	0.999	1.334	0.929
Spain	3.240	−0.049	0.999	2.991	0.394
Sweden	1.162	−0.022	0.993	0.808	0.683
Switzerland	1.712	−0.011	0.992	1.324	0.144
Turkey	1.405	0.000	0.612	3.350	0.000
U.K.	6.072	−0.134	0.945	0.389	0.975
USA	3.061	−0.010	0.996	1.892	0.282

Korea introduced a similar subsidy policy for the installment of solar thermal systems in domestic households.

Despite the similar policies and the fact that Germany is a leading country in the area of renewable energy, there are important differences between Germany and Korea. First, Germany has implemented more aggressive policies, such as the Renewable Energy Sources Act (EEG) and Renewable Energies Heat Act (EEWärmeG) than Korea. These regulations strictly control market prices and the portion of heating systems based on renewable energy sources. Moreover, Germany has a successful history of implementing policies and promoting related industries,

whereas Korea has lagged behind in initiating renewable energy policies.

As briefly discussed here, qualitative as well as quantitative knowledge of parameters such as distance and closeness can help select the best candidate for an analogy approach. However, it is challenging to fully integrate details of the policy, culture, history, and market environment of each country into such an analysis. Furthermore, even with abundant materials, it is difficult to compare these in an objective manner. We therefore focused on measurable aspects; our results suggest that Germany is a good analogous case for the future Korean renewable energy market.

4.2. Relation between investment and penetration rate

Before proposing a rational investment plan for Korea, the relation between investment and penetration rate of renewable energy should be investigated. Using the procedure shown in Fig. 1, we first determined the relationship based on realized data from the benchmark market of Germany (this subsection), and then applied it in inverse function form to the Korean market (next subsection).

To identify the overall relation, we prepared a scatter plot of renewable energy penetration rate against cumulative investment. To increase the amount of data, we used the estimated annual penetration rates shown in Fig. 5. R&D investment data were divided by the annual GDP data (collected from "World Economic Outlook Database" [34]) to reflect the economic scale and growth. To this end, cumulative investment was assessed as follows:

$$\text{cumulative investment}_t = \sum_{i=1}^{t} \frac{\text{annual investment}_i}{\text{annual GDP}_i} \qquad (4)$$

The relation between cumulative investment and penetration shown in Fig. 7 is consistent with the description of Afuah [9]: an S-shaped curve with investment or aggregated effort placed in a technology as an input variable. This motivated us to model the relation as a logistic model by substituting time with cumulative investment. In general, the effect of investment in a market is only seen after a certain length of time. In accordance with this, Lee et al. [35] proposed a diffusion model with a 4-year time lag. Similarly, we formulated a logistic model of penetration rate

Table 4
Estimated penetration rates and absolute percentage errors.

	Belgium	Czech	Denmark	Germany	Hungary	Ireland	Netherlands	Poland	Slovakia	U.K.
Estimated (%)	4.60	6.61	21.58	10.23	7.46	5.48	4.18	7.60	7.28	3.96
Error (%)	6.40	4.39	10.58	0.77	3.54	5.52	6.82	3.40	3.72	7.04
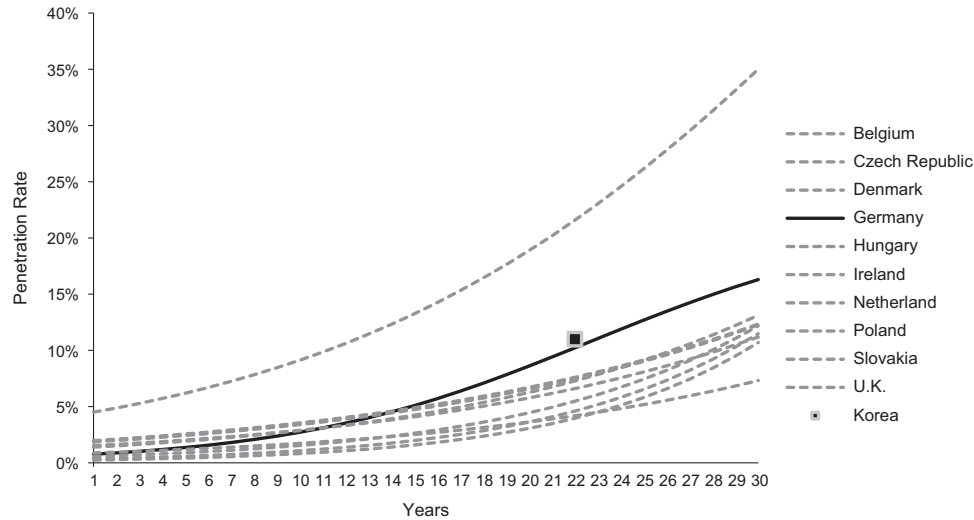
Fig. 6. Estimated penetration curves and the target level of the Korean plan.

Table 5
Distance in parameters between candidate countries and Korea.

	Belgium	Czech	Denmark	Germany	Hungary	Ireland	Netherlands	Poland	Slovakia	U.K.
Distance	4.118	3.431	2.847	1.918	3.381	3.749	2.629	3.381	3.371	4.287
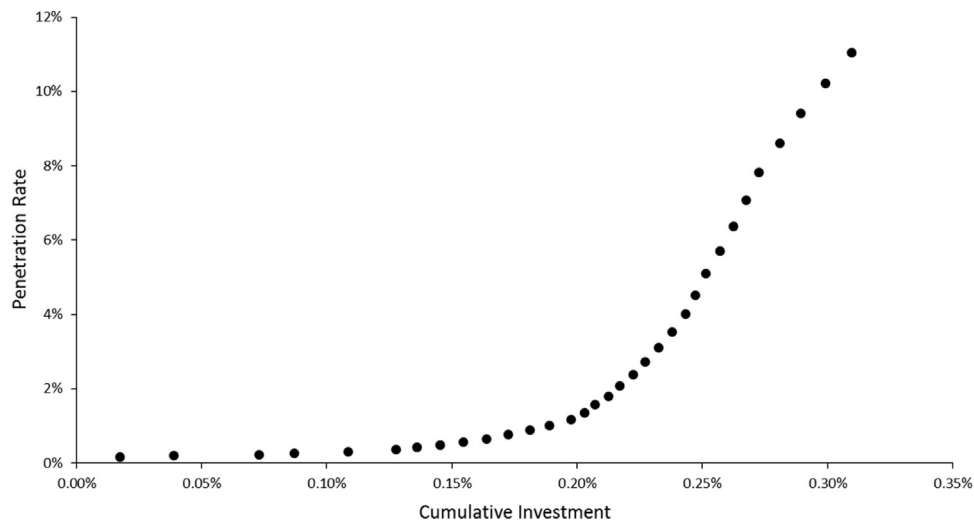
Fig. 7. Scatter plot of penetration rates against cumulative investment to GDP in Germany.

versus cumulative investment as follows:

$$Y_t = \frac{m}{1 + e^{a + bX_{t-L}}} \quad (5)$$

where Y_t is the penetration rate at year t, and X_{t-L} is the cumulative investment at $t-L$, where L is the time lag (set as 3–5 years). For all three models, parameters and estimated curves

were obtained by the NLS method with the market potential restricted to 21.71% as described in Table 3.

As shown in Table 6 and Fig. 8, there were no noticeable differences among models incorporating the predetermined lags. Though the lag-3 was the best model when fitness was considered, gaps were insignificant and slight; all three models had adjusted R^2 values higher than 99%. This result suggests that the

proposed model successfully explains the relation between investment and penetration rate.

4.3. Investment plan for Korea

Finally, we determined an appropriate investment plan for Korea based on the previous results. We applied the inverse function of the relation in Eq. (5) to derive annual investments as shown below:

$$X_{t-L} = \frac{1}{b} \ln\left(\frac{m - Y_t}{Y_t}\right) - a \tag{6}$$

Using the annual target penetration rates as estimated in Table 2 and Fig. 5, and the parameters shown in Table 6, we calculated the required annual and cumulative investment scales to attain the target penetration rates with respect to all three lag times (3 to 5 years).

The annual investment trend increased slightly over the entire analysis period, as depicted in Table 7 and Fig. 9. Thus, cumulative investments followed an almost linear upward trend curve. This implies that consistent investment is necessary to increase penetration of renewable energy and to satisfy the target level of the government plan.

Compared to the announced investment plan, the derived plan started at a high cumulative expenditure level. The government plan schedule also increased steeply to exceed the estimated curves around 2020. Considering that there are usually several years of lag between input of resources and industry progress, the original schedule might fail to impact the market in a sufficiently timely manner to meet the goal.

To verify the investment plans shown in Fig. 9, we calculated penetration rates according to the relationship in Eq. (6). The results are shown in Table 8 and Fig. 10; there was a significant

delay associated with the government plan. Based on the results of this paper, we predict that if Korea follows the proposed government investment schedule, renewable energy will only be provided at half the target level of 11% by 2035.

Differences between investment plans based on the obtained logistic curve of the investment-penetration rate relation are shown in Fig. 11. The solid line illustrates the relation deduced in Fig. 8 and Eq. (5), implying a 4-year time lag. The three gray squares correspond to the government investment plan (as shown in Fig. 9); results were estimated from the logistic model. Though the scales of investment in those two plans are similar, the consequences are dramatically different, as shown in Fig. 10. If Korea persists with the government plan in its current form, renewable energy will not account for a significant share of the energy market.

Another factor that may contribute to the inability of the proposed government plan to reach its target goal is the tipping points of the diffusion curve. As noted in Section 3.2 and shown in Fig. 5, an S-shaped logistic diffusion curve usually has some tipping points. Particularly, takeoff and peak points indicate two

Table 6
Estimation results for the investment-penetration relation model.

Lag(years)	a	b	M	ln(SSE)	Adj. R^2
3	7.992	−2876.1	0.2171	0.1053	0.9952
4	7.916	−2908.8	0.2171	0.2995	0.9939
5	7.681	−2873.0	0.2171	0.5592	0.9918

Table 7
Required investment scale to attain the target penetration rate.

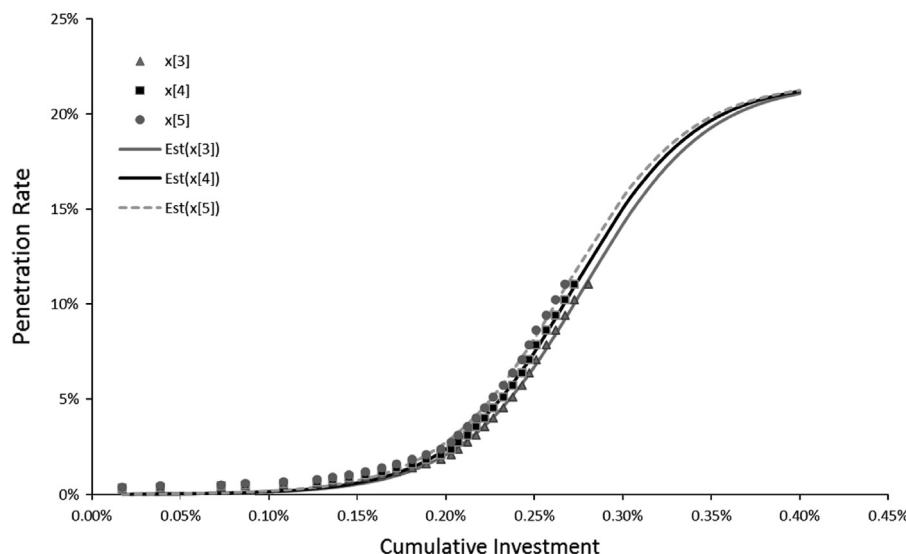| Year	Cumulative investment (m$)			Annual investment (m$)		
	Lag 3	Lag 4	Lag 5	Lag 3	Lag 4	Lag 5
2013	2164.7	2061.4	2047.1	47.8	46.9	47.2
2014	2213.5	2109.4	2095.4	48.8	48.0	48.3
2015	2263.5	2158.5	2144.8	50.0	49.1	49.4
2016	2314.7	2208.8	2195.0	51.2	50.2	50.2
2017	2367.0	2259.9	2246.4	52.3	51.1	51.4
2018	2420.3	2312.2	2298.7	53.2	52.3	52.3
2019	2474.7	2365.4	2351.9	54.5	53.2	53.2
2020	2530.2	2419.5	2406.0	55.5	54.1	54.1
2021	2586.6	2474.5	2460.9	56.4	55.0	54.9
2022	2643.9	2530.4	2516.6	57.3	55.9	55.7
2023	2702.1	2587.1	2572.8	58.2	56.6	56.3
2024	2761.1	2644.3	2629.8	59.0	57.2	57.0
2025	2820.7	2702.2	2687.1	59.6	57.9	57.3
2026	2881.1	2760.5	2744.8	60.4	58.3	57.7
2027	2941.8	2819.2	2802.9	60.7	58.7	58.1
2028	3003.0	2878.3	2861.0	61.2	59.1	58.0
2029	3064.5	2937.4	2919.1	61.5	59.1	58.1
2030	3126.0	2996.5	2977.0	61.5	59.1	57.9

Fig. 8. Estimated logistic curves of the relation between investment and penetration rate.
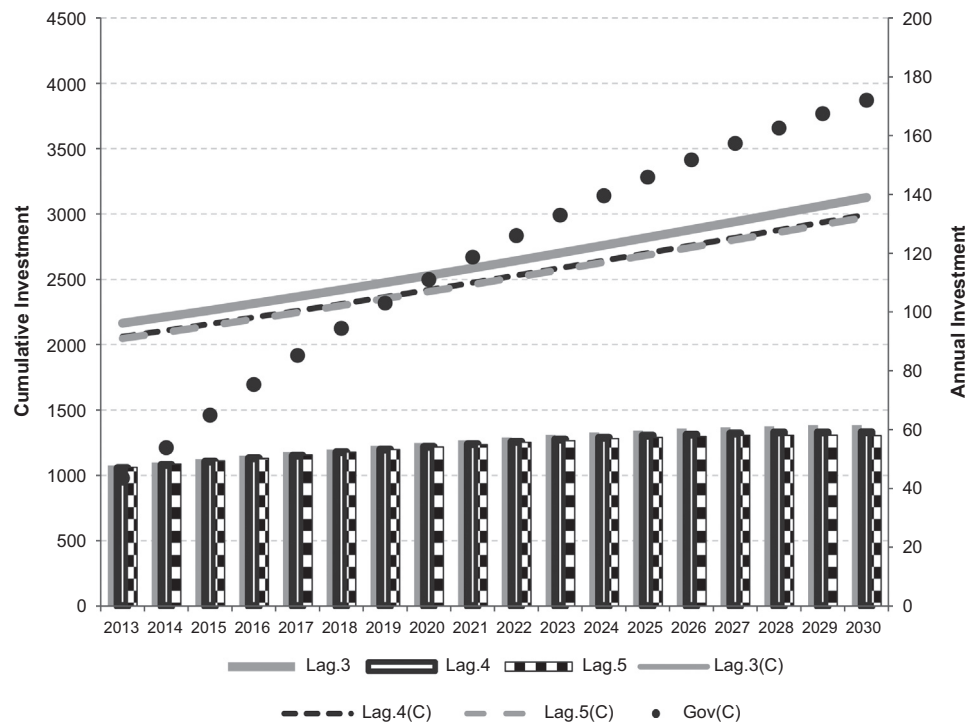
Fig. 9. Comparison of investment scales. Annual investments (derived): bars; left axis, cumulative investment (derived): lines; right axis, cumulative investment (government plan): squares; right axis.

Table 8
Comparison of penetration rates.

Year	Penetration by derived investment			Penetration by government plan	
	Lag 3 (%)	Lag 4 (%)	Lag 5 (%)	Investment plan (%)	Goal (%)
2013	3.46	3.46	3.50	0.00	
2014	3.80	3.81	3.77	0.00	
2015	4.18	4.19	4.14	0.00	4.3
2016	4.48	4.50	4.53	0.10	
2017	4.90	4.93	4.85	0.10	
2018	5.35	5.27	5.30	0.10	
2019	5.70	5.74	5.77	0.20	
2020	6.20	6.12	6.14	0.40	6.1
2021	6.59	6.64	6.66	0.60	
2022	7.13	7.05	7.07	0.80	
2023	7.55	7.62	7.63	1.20	
2024	7.98	8.06	8.06	1.60	
2025	8.57	8.50	8.50	2.10	
2026	9.02	9.11	9.10	2.70	
2027	9.48	9.58	9.56	3.40	
2028	10.10	10.05	10.02	4.10	
2029	10.56	10.52	10.49	4.90	
2030	11.03	10.99	10.96	5.70	11.0

major milestones in the early stages of diffusion of a service or product. The gray squares were left-shifted compared to the white circles. The first two gray squares were not even close to the takeoff (dashed vertical line), while the last one was between the takeoff and peak (solid vertical line). These differences imply that the announced investment plan is not sufficient to trigger a change in the energy market. In contrast, for our suggested investment schedule, all cumulative investments exceed the takeoff point in 2015, and the last one in 2030 even passes the peak point, which appears be a requirement for the investment scale to achieve the target penetration rate of 11%.

Additionally, we conducted a sensitivity analysis to examine the robustness of the derived investment plan. Based on the 4-year lag model, a 1% deviation in investment scale for both directions was tested, resulting in varied penetration rates. Fig. 12 suggests

that the estimated output of the derived plan is robust with regards to the investment scale, such that a 1% change in cumulative investment yields only a 0.4% change in penetration rate in 2030.

5. Conclusions

Despite rapid progress in renewable energy around the world, Korea has lagged behind other developed countries. In response to this shortcoming, Korea has devised and executed plans to advance renewable energy. Our purpose in this study was to establish a rational investment plan to ensure that the desired development level is met. To address the lack of historical data in Korea, we adopted an analogous approach by selecting an OECD country with similar technology and industry precedents as Korea. Germany was selected as the benchmark based on the similarity in diffusion processes between Germany and Korea. We analyzed the effect of investment on the penetration rate in the form of a logistic function and established an investment plan by applying the relation to the announced plan. Our results suggest that the market needs a considerably larger investment than that proposed by the government to invigorate the market if the target penetrance of 11% for renewable energy is to be met in 2030.

The main contributions of this study are as follows. First, we proposed a practical procedure for establishing an investment plan (particularly for followers or developing markets). This procedure is rational as well as easy to implement. Second, we utilized the analogy method to overcome the absence of data. Finally, we used a logistic model to describe the characteristics of the technology. The selected diffusion model not only allows estimation of the diffusion of penetration rates, but also allows assessment of the impact of investments on the market.

Because we proposed a procedure to establish an investment plan based on an empirical case study, it would be interesting to apply this methodology to other technologies and industries. We limited the analogy approach to quantitative aspects represented
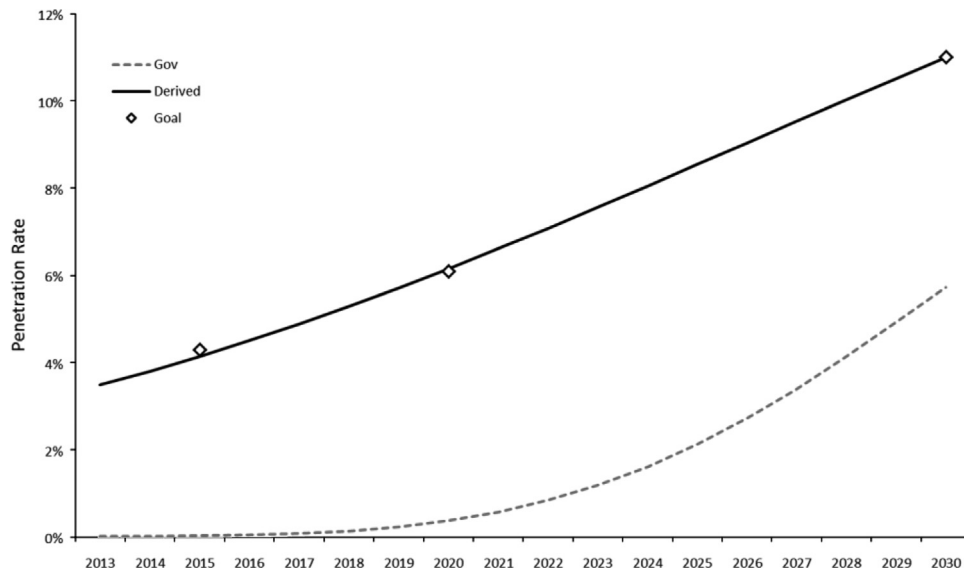
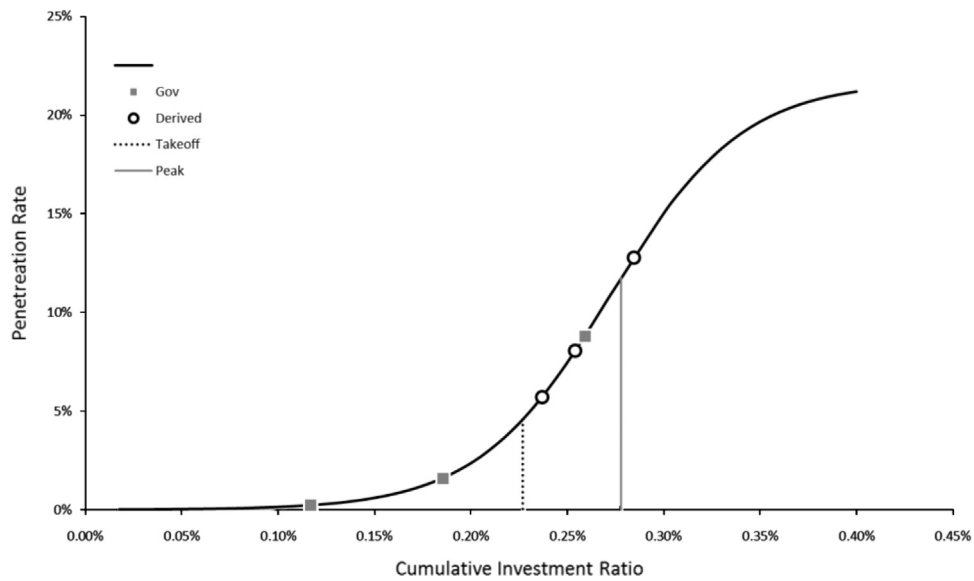**Fig. 10.** Comparison of derived and government investment plans (2010–2030).

Fig. 11. Comparison of derived and announced investment plans versus cumulative investment. Gray squares (white circles): results from government (derived) investment plan by 2015, 2020, 2030, *X*-axis: cumulative investment ratio with respect to GDP, *Y*-axis: penetration rate of renewable energy.
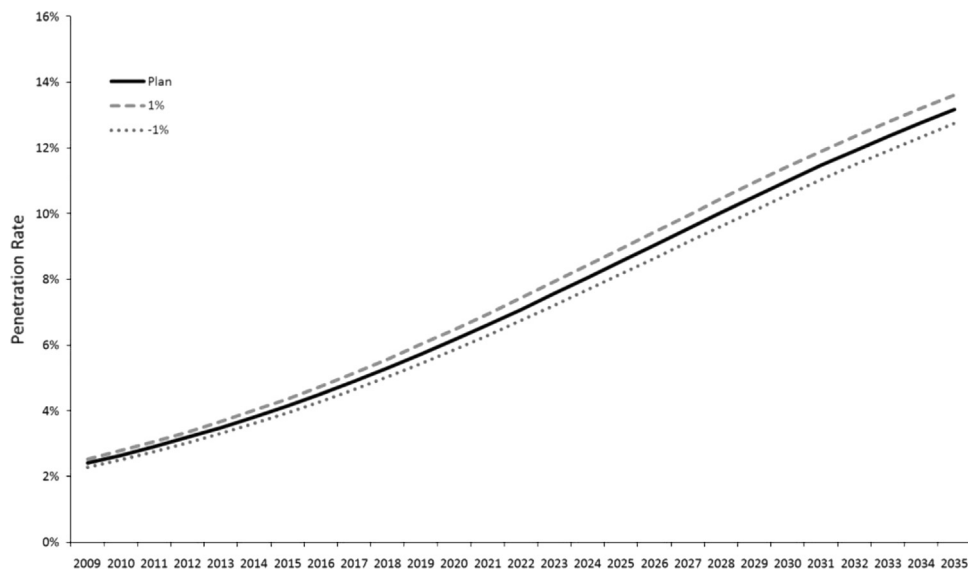

Fig. 12. Sensitivity analysis of penetration rate with respect to investment.

by the diffusion patterns. However, because qualitative aspects such as policies, regulations, history, and characteristics of candidate markets are also important factors that contribute to market prospects, it would be worthwhile to extend our research by incorporating these factors into the analysis. Furthermore, the management implications of our proposed investment plan should be determined by a comparative analysis of relevant policies and their outcomes across different countries.

Acknowledgments

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